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A technique for evaluation of track loss probability and estimation error during track maintenance in clutter has been developed. The technique can be used for the selection of detection threshold to optimize the overall performance of a detection tracking system.

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19. ABSTRACT

In this report we deal with the following topics:

1. DETECTION THRESHOLD SELECTION FOR TRACKING PERFORMANCE OPTIMIZATION
2. A RECURSIVE MULTIPLE MODEL APPROACH TO NOISE IDENTIFICATION
3. AN IMM APPROACH FOR TARGET TRACKING WITH GLINT NOISE
4. BALLISTIC MISSILE TRACK INITIATION FROM SATELLITE OBSERVATIONS
5. BEAM POINTING CONTROL OF A PHASED ARRAY RADAR FOR MANEUVERING TARGET TRACKING
6. NONLINEAR STABILIZATION OF JUMP LINEAR GAUSSIAN SYSTEMS
7. ADAPTIVE DETECTION THRESHOLD OPTIMIZATION FOR TRACKING IN CLUTTER
8. IMAGE SEGMENTATION BASED ON OPTIMAL LAYERING FOR PRECISION TRACKING
9. A GENERALIZED S-DIMENSIONAL ALGORITHM FOR MULTISENSOR MULTI-TARGET STATE ESTIMATION
10. TARGET MOTION ANALYSIS IN CLUTTER FOR PASSIVE SONAR USING AMPLITUDE INFORMATION
11. IMMPDA ESTIMATOR FOR BEAM POINTING CONTROL OF A PHASED ARRAY RADAR IN THE PRESENCE OF FA AND ECM
12. MATSurv: A MULTISENSOR AIR TRAFFIC CONTROL SURVEILLANCE SYSTEM
13. STABILIZATION OF JUMP LINEAR GAUSSIAN SYSTEMS WITHOUT MODE OBSERVATIONS
14. DISCRETE-TIME MARKOV REWARD MODELS: RANDOM REWARDS
15. MOMENT RECURSIONS OF THE CUMULATIVE PERFORMANCE OF PRODUCTION SYSTEMS USING DISCRETE-TIME MARKOV REWARD MODELS
16. TRACKING AND FUSION WITH MULTIPLE MTI SENSORS
17. BALLISTIC MISSILE TRACK INITIATION FORM SATELLITE OBSERVATIONS
18. PERFORMANCE PREDICTION OF HYBRID STATE ALGORITHMS: THE SCENARIO CONDITIONAL AVERAGING APPROACH
19. MULTITARGET-MULTISENSOR TRACKING: PRINCIPLES AND TECHNIQUES
20. JOINT PROBABILISTIC DATA ASSOCIATION IN DISTRIBUTED SENSOR NETWORKS

0. INTRODUCTION

This report summarizes the results obtained during the period of the Grant. The topics are divided according to the publications generated from the research effort. (only items published since 3-1-94 or in press are listed).

Sections 1 and 7 deal with the use of discrete-continuous optimization techniques for the selection of a signal processing parameter such that the (downstream) tracking performance is optimal.

The identification of stationary or nonstationary noise intensities is the topic of Section 2.

A scheme for reducing the effect of glint noise (when tracking targets at short range) is discussed in Section 3.

Sections 4 and 17 (the latter an expanded version, invited as a chapter for a forthcoming AGARDOGRAPH) show how one can successfully initialize ballistic missile tracks using a single satellite-based passive sensor.

Sections 5 and 11 show how one can minimize the radar energy when tracking highly maneuvering targets, even in the presence of electronic countermeasures. This is in the process of transitioning to NSWC for an Aegis type system.

The stabilization of stochastic hybrid systems with partial observations is the topic of Sections 6 and 13.

An image processing (segmentation) technique developed for target centroid tracking is presented in Section 8; this has been transitioned to the ARROW ABM.

Sections 9 and 12 present assignment algorithms for tracking; this has been transitioned to Rome Laboratory.

The use of a passive sensor (sonar or IR) for target localization and the corresponding CRLB are the topics of Section 10.

Sections 14 and 15 deal with the use of discrete optimization in manufacturing systems.

Multisensor fusion is the topic of Section 16 (an invited chapter in a forthcoming AGARDOGRAPH).

Tracking system performance prediction without Monte Carlo runs is discussed in Section 18 for hybrid systems.

The textbook briefly described in Section 19 describes the state of the art in Multitarget-Multisensor tracking.

The book chapter summarized in Section 20 deals with a distributed sensor network.

1. DETECTION THRESHOLD SELECTION FOR TRACKING PERFORMANCE OPTIMIZATION
X.R. Li and Y. Bar-Shalom, IEEE Trans. on Aerosp. and Electronic Systems, Vol. 30, No. 3, July 1994.

A technique for the evaluation of the track loss probability and the estimation error during track maintenance in clutter has been developed recently by the authors. This work overcomes the limitation of an earlier technique that does not handle the transient process of tracking divergence. Track loss, being a "runaway" phenomenon, clearly requires transient evaluation capability. The new technique provides, without the need for expensive Monte Carlo simulations, the probability that a track is maintained in the presence of all sources of uncertainty encountered in a tracking process. This technique is of a hybrid nature; it involves explicit probabilistic accounting of both the continuous and the discrete uncertainties. Here it is demonstrated how this technique can be used for the selection of the detection threshold to optimize the overll performance of a detection-tracking system.

2. A RECURSIVE MULTIPLE MODEL APPROACH TO NOISE IDENTIFICATION
X.R. Li and Y. Bar-Shalom, IEEE Trans. on Aerosp. and Electronic Systems, Vol. 30, No. 3, July 1994.

Correct knowledge of noise statistics is essential for an estimator or controller to have reliable performance. In practice, however, the noise statistics are unknown or not known perfectly and thus need to be identified. Previous work on noise identification is limited to stationary noise and noise with slowly varying statistics only. An approach is presented here that is valid for nonstationary noise with rapidly or slowly varying statistics as well as stationary

noise. This approach is based on the estimation with multiple hybrid (discrete/continuous) system models. As one of the most cost-effective estimation schemes for hybrid systems, the interacting multiple model (IMM) algorithm is used in this approach. The IMM algorithm has two desirable properties: it is recursive and has fixed computational requirements per cycle. The proposed approach is evaluated via a number of representative examples by both Monte Carlo simulations and a nonsimulation technique of performance prediction developed by the authors recently. The application of the proposed approach to failure detection is also illustrated.

3. AN IMM APPROACH FOR TARGET TRACKING WITH GLINT NOISE
E. Daeipour and Yaakov Bar-Shalom, Trans. Aerosp. Electronic Systems, AES-31, April 1995. Also in Proc. 1994 IEEE National Radar Conf., Atlanta, GA March 1994.

The application of the interacting multiple model (IMM) estimation approach to the problem of target tracking when the measurements are perturbed by glint noise is considered. The IMM is a very effective approach when the system has discrete uncertainties in the dynamic or measurement model as well as continuous uncertainties. It is shown that this method performs better than the "score function" method. It is also shown that the IMM method performs robustly when the exact prior information of the glint noise is not available.

4. BALLISTIC MISSILE TRACK INITIATION FROM SATELLITE OBSERVATIONS
M. Yeddanapudi, Y. Bar-Shalom, S. Deb and K.R. Pattipati, Trans. Aerosp. Electronic Systems, AES-31, 1995. Also in Proc. SPIE Conf. Signal and Data Processing of Small Targets (#2235), Orlando, FL, 1994.

This paper presents an algorithm to initiate tracks of a

ballistic missile in the initial exoatmospheric phase, using line of sight measurements from one or more moving platforms (typically satellites).

The Gauss-Newton iterative least squares minimization algorithm for estimating the state of a nonlinear deterministic system with nonlinear noisy measurements has been previously applied to the problem of angles-only orbit determination using more than three observations. A major shortcoming of this approach is that convergence of the algorithm depends strongly on the initial guess. By using the more sophisticated Levenberg-Marquardt method in place of the simpler Gauss-Newton algorithm and by developing robust new methods for obtaining the initial guess, the above mentioned difficulties have been overcome. In addition, an expression for the Cramer-Rao lower bound on the error covariance matrix of the estimate is derived. We also incorporate additional partial information as an extra pseudo-measurement and determine a modified maximum likelihood estimate of the target state and the associated bound on the covariance matrix.

Monte Carlo simulation studies on some typical scenarios were performed, and the results indicate that the estimation errors are commensurate with the theoretical lower bounds, thus illustrating that the proposed estimators are efficient.

5. BEAM POINTING CONTROL OF A PHASED ARRAY RADAR FOR MANEUVERING TARGET TRACKING
E. Daeipour, Y. Bar-Shalom and X.R. Li, Proc. 1994 American Control Conf., Baltimore, MD, June 1994.

The design and performance of an Interacting Multiple Model (IMM)

estimator for a given benchmark problem of highly maneuvering targets are presented in this paper. The design parameters of the IMM estimator as well as an adaptive sampling policy are described. It is shown tha the IMM estimator with adaptive sampling policy has a better performance in terms of the average track loss, average dwells per run and noise reduction in non-maneuvering periods of time than the best Kalman filter.

6. NONLINEAR STABILIZATION OF JUMP LINEAR GAUSSIAN SYSTEMS
G. Pan and Y. Bar-Shalom, Proc. 1994 American Control Conf., Baltimore, MD, June 1994.

This paper considers jump linear (JL) systems under the assumption that the mode (system model) is not directly observed. In this situation, the optimal control and stabilization problems are nonlinear (dynamic) optimization problems and very difficult due to the dual effect. Assuming that the base state is perfrectly measured, this work answers the following question positively: If the JL system is stabilizable by a linear feedback control, can one find a better stabilizing controller? Two such nonlinear control schemes are presented. For the case of an unknown parameter problem, an example is given to show that the cost from using a nonlinear stabilizing controller derived here is within a few percent from a lower bound of the (unknown) optimal cost, and is about half of the cost of using an algorithm from the literature, due to Saridis.

7. ADAPTIVE DETECTION THRESHOLD OPTIMIZATION FOR TRACKING IN CLUTTER
(S.B. Gelfand, T.E. Fortmann and Y. Bar-Shalom, IEEE Trans. Aerosp. Electronic Systems, AES-32, Jan. 1996).

This paper presents a method for minimizing the probabilistic

data association filter (PDAF) tracking error by adjusting the threshold used in the detection of candidate targets in the validation region. Furthermore, the modeling of the validation region as a collection of resolution cells, rather than as a continuum, is novel.

8. IMAGE SEGMENTATION BASED ON OPTIMAL LAYERING FOR PRECISION TRACKING
A.K. Kumar, Y. Bar-Shalom and E. Oron, Proc. DIMACS Workshop on Partitioning Data Sets, 1994.

We present a method for precision tracking of a low observable target based on data obtained from imaging sensors. The image is assumed to consist of gray level intensities in each pixel. The intensity range is divided into a target layer and background layers. A binary image is obtained and grouped into clusters using image segmentation techniques. Using the centroid measurements of the clusters, the Probabilistic Data Association Filter (PDAF) is employed for tracking the centroid of the target.

The boundaries of the target layer are optimized by minimizing the Bayes risk. A closed-form analytical expression is obtained for the single frame-based centroid measurement noise variance.

The simulation results presented validate both the expression for the measurement noise variance as well as the performance predictions of the proposed tracking method. The method is first illustrated on a dim synthetic target occupying about 80 pixels within a 64 x 64 frame in the presence of noise background which can be stronger than the target. The usefulness of the method for practical applications

is demonstrated for a highway traffic surveilance problem by considering a sequence of real target images (a moving car) of about 20 pixels in size, in a noisy urban environment.

This technique has been transitioned into the ARROW ABM.

9. A GENERALIZED S-DIMENSIONAL ALGORITHM FOR MULTISENSOR MULTI-TARGET STATE ESTIMATION
S. Deb, K.R. Pattipati, Y. Bar-Shalom and M. Yeddanapudi, Proc. 31st IEEE Conf. Decision and Control, Orlando, FL, Dec. 1994. Also to appear in IEEE Trans. Aerosp. Electronic Systems.

In this paper we present a fast near-optimal assignment algorithm to solve a generalized multidimensional assignment problem. Such problems arise in surveillance systems estimating the position of an unknown number of targets. The central problem in a multisensor-multitarget state estimation problem is that of data association - the problem of determining from which target, if any, a particular measurement originated. The data-association problem is formulated as a generalized S-dimensional (S-D) assignment problem, which is NP-hard for 3 or more sensor scans ($S \geq 3$). In this paper, we present an efficient and recursive generalized S-D assignment algorighm ($S \geq 3$) with application to the localization of unknown number of emitters using multiple high frequency direction finders.

This technique has been transitioned into an HFDF being developed by SWRI (San Antonio, TX).

10. TARGET MOTION ANALYSIS IN CLUTTER FOR PASSIVE SONAR USING AMPLITUDE INFORMATION
T. Kirubarajan and Y. Bar-Shalom, Proc. 1995 American Control Conf., Seattle, WA, June 1995.

In conventional passive and active sonar systems, target

amplitude information (AI) at the output of the signal processor is used only to declare detections and provide measurements. We show that the AI can be used in passive sonar systems, with or without frequency measurements, in the estimation process itself to enhance the performance in the presence of clutter, i.e., in a low SNR situation, when the target-originated measurements cannot be identified with certainty. A probabilistic data association based maximum likelihood estimator for target motion analysis that uses amplitude information is derived. A track formation algorithm and the Cramer-Rao lower bound in the presence of false measurements, which is met by the estimator even under low SNR conditions, are also given. Results demonstrate improved accuracy and superior global convergence when compared to the estimator without amplitude information. These results also apply to IR sensors.

11. IMMPDA ESTIMATOR FOR BEAM POINTING CONTROL OF A PHASED ARRAY RADAR IN THE PRESENCE OF FA AND ECM
T. Kirubarajan, Y. Bar-Shalom, and E. Daeipour, Proc. 1995 American Control Conf., Seattle, WA, June 1995.

In this paper, the use of the Interacting Multiple Model (IMM) estimation algorithm combined with the Probabilistic Data Association Filter (PDAF) for adaptive beam pointing control of a phased array radar to track maneuvering targets in the presence of false alarms and Electronic Counter Measures (ECM) is presented. The tracking algorithm includes target track formation and maintenance using IMMPDAF, jammer tracking using an IMM estimator and the adaptive selection of sampling period. Simulation results show the usefulness of using IMMPDAF, in terms of radar energy, average track loss, average dwells and noise reduction.

12. MATSurv: A MULTISENSOR AIR TRAFFIC CONTROL SURVEILLANCE SYSTEM
M. Yeddanapudi, Y. Bar-Shalom and K.R. Pattipati, Proc. SPIE Conf. Signal and Data Processing of Small Targets, San Diego, CA, 1995.

In this paper we present the design and implementation of MATSurv - an experimental Multisensor Air Traffic Surveillance (ATS) system. The proposed system consists of a Kalman filter based state estimator used in conjunction with a two dimensional (2-D) sliding window assignment algorithm.

The performance of the proposed system is illustrated on a measurement database from two FAA radars which contains detections of targets that were in a variety of trajectories. The results obtained indicate that the proposed system provides a superior classification of the measurements into tracks (i.e., trajectories of the most likely targets) compared to the target trajectories obtained using the measurement IDs. The multiplicity of targets assigned to the same ID prevents the exclusive reliance on the target ID, and its use in evaluating the performance of the association algorithm is clearly inappropriate. A particular track formed by the association algorithm has, in general, a few measurements less than the corresponding target trajectory obtained using the IDs. This is primarily due to the fact that the association algorithm rejects measurements (i.e., outliers) that deviate considerably from an established track. Discarding these measurements yields a better estimate of the trajectory than the one obtained by including these outlying measurements. In addition, this algorithm has been shown to be capable of "unscrambling" mixed up transponder responses with

switched IDs between two neighboring targets.

This technique has been transitioned to Rome Laboratory.

13. STABILIZATION OF JUMP LINEAR GAUSSIAN SYSTEMS WITHOUT MODE OBSERVATIONS
G. Pan and Y. Bar-Shalom, Intn'l J. Control, 1986. Also in Proc. 1995 European Control Conf., Rome, Italy, Sept. 1995.

Systems, such as those subject to abrupt changes (including failure) or those with uncertain dynamic model (or more than one possible model), can be naturally modeled as Jump Linear (JL) systems. Due to their applications in the fields like tracking, fault-tolerant control, manufacturing process and robots etc., JL systems have drawn extensive attention. The optimal control/ stabilization problem for JL systems, when the mode (system model) is not assumed to be directly and perfectly observed, a realistic assumption in many applications, is nonlinear and prohibitive both analytically and computationally due to the dual effect. In this work, we first present the optimal controller assuming a certain type of mode availability. Using this optimal feedback gain, we derive a condition that ensures the stabilizing property for a class of adaptive controllers without direct knowledge of the mode. Two specific adaptive controllers (maximum a posteriori and averaging) are examined in detail and their stabilizing property is proved. An algorithm to compute the optimal feedback gain and its convergence are presented. Examples show that the performance of the adaptive controllers without mode observations derived here is very close to that of the optimal controller with known modes.

14. DISCRETE-TIME MARKOV REWARD MODELS: RANDOM REWARDS
R. Mallubhatala and K.R. Pattipati, Proc. of Rensselaer's fourth Intl. Conf. on Computer Integrated Manufacturing and Automation Technology, 1994.

In this paper, we consider the discrete-time version of performability modeling, when the Markov rewards are random. The discrete-time approach is well-suited for the performance studies of Automated Manufacturing Systems (AMS) in the presence of failures, repairs and reconfigurations. AMS exist in various configuration states and this transitional behavior is modeled using discrete-time Markov chains. In addition, the performance in each configuration state is modeled by a Markov reward structure. The random reward structure used resembles more closely the behavior of actual systems than the deterministic models used in earlier literature. In this paper, we derive recursive expressions for the conditional densities and moments of the cumulative performance function, when the underlying Markov chain describing the evolution of the configuration states is homogenous. An example is used to illustrate the methods obtained in this paper.

15. MOMENT RECURSIONS OF THE CUMULATIVE PERFORMANCE OF PRODUCTION SYSTEMS USING DISCRETE-TIME MARKOV REWARD MODELS
R. Mallubhatla, K.R. Pattipati, N. Viswanadham, Proc. of the 1994 IEEE Conf. on Robotics & Automation.

In this paper, we use discrete-time Markov reward models to obtain moment recursions of the cumulative performance of an Automated Manufacturing System (AMS). An AMS can be in various

structure states due to failures, repairs and reconfigurations of its components. This multi-state behavior is modeled using a Markov reward structure that is similar to the continuous-time version. This methodology can also be used to compute other performance measures, such as the expected in-process inventory and the expected production per unit time. A three-stage transfer line with finite buffers is used to illustrate the methods obtained in the paper.

16. TRACKING AND FUSION WITH MULTIPLE MTI SENSORS
K.C. Chang and Y. Bar-Shalom, in AGARDOGRAPH on Multisensor-Multi-target Data Fusion, Tracking and Identification, 1995.

Multisensor tracking and data fusion deals with combining data from various sources to arrive at an accurate assessment of the situation. Technical difficulties in performing multisensor tracking and fusion include not only ambiguous data, but also disparate data sources. The tracking and fusion problem is further complicated by the facts that targets may not be detected by some sensors, dense false alarms and clutter detections may be present, or the target model may not be known exactly. In this chapter, a multitarget tracking problem which involves data obtained from multiple MTI radars is considered. A tracking and fusion algorithm which takes into account the uncertainties in both data origin and target dynamics under a dense clutter environment is presented.

17. BALLISTIC MISSILE TRACK INITIATION FORM SATELLITE OBSERVATIONS
M. Yeddanapudi, Y. Bar-Shalom, S. Deb and K.R. Pattipati, in AGARDOGRAPH on Multisensor-Multi-target Data Fusion, Tracking and Identification, 1995.

This paper presents an algorithm to initiate tracks of a

ballistic missile in the initial exoatmospheric phase, using line of sight measurements from one or more moving platforms (typically satellites). The major feature of this problem is the poor target motion observability which results in a very ill-conditioned estimation problem.

The Gauss-Newton iterative least squares minimization algorithm for estimating the state of a nonlinear deterministic system with nonlinear noisy measurements has been previously applied to the problem of angles-only orbit determination using more than three observations. A major shortcoming of this approach is that convergence of the algorithm depends strongly on the initial guess. By using the more sophisticated Levenberg-Marquardt method in place of the simple Gauss-Newton algorithm and by developing robust new methods for obtaining the initial guess in both single and multiple satellite scenarios, the above mentioned difficulties have been overcome. In addition, an expression for the Cramer-Rao lower bound on the error covariance matrix of the estimate is derived.

We also incorporate additional partial information as an extra pseudo-measurement and determine a modified maximum likelihood estimate of the target state and the associated bound on the covariance matrix. In most practical situations, probabilistic models of the target altitude and/or speed at the initial point constitute the most useful additional information.

Monte Carlo simulation studies on some typical scenarios were performed, and the results indicate that the estimation errors are commensurate with the theoretical lower bounds, thus illustrating that the proposed estimators are efficient.

18. PERFORMANCE PREDICTION OF HYBRID ALGORITHMS
X.R. Li and Y. Bar-Shalom, International Series on Advances in Control and Dynamic Systems, (C.T. Leondes, Ed), Academic Press, 1995.

Algorithms that involve both continuous-valued and discrete-valued uncertainties are referred to as hybrid algorithms. These algorithms can usually be best understood in the framework of an important class of (stochastic) systems with both continuous-valued and discrete-valued (random) variables - the so-called (stochastic) hybrid systems.

A hybrid system, with discrete-valued as well as continuous-valued variables, provides a framework particularly powerful for solving problems characterized by structural as well as parametric changes and for decomposition of a complex system into simpler subsystems.

19. MULTITARGET-MULTISENSOR TRACKING: PRINCIPLES AND TECHNIQUES
(Y. Bar-Shalom and X.R. Li, YBS Publishing, 1995).

These lecture notes in textgraph format - a completely self-contained text suitable for use as viewgraphs as well - cover the topic of the estimation of the states of targets in a multitarget-multisensor environment.

This problem is characterized by measurement origin uncertainty - typical for low observables - in addition to the usual noises in the state equations. Such a situation occurs in an environment where there is clutter or the false alarm rate is high or due to the presence of several targets in the same neighborhood.

The tools for evaluation and design of algorithms for the association of measurements and tracking are presented. Explicit

consideration is given for measurements obtained from different sensors. These techniques form the basis for the design of automated decision systems in a multitarget-multisensor situation. The modeling accounts for target maneuvers, detection probability, false alarms, interference from other targets and the finite resolution capability of sensors.

The problems of track initiation, track maintenance and track-to-track association and fusion in a multisensor situation are considered. The optimization of certain signal processing parameters based on tracking performance is also discussed.

Many of these techniques have applications to state estimation when using multiple sensors in control systems, e.g., autonomous vehicles and robotics.

20. JOINT PROBABILISTIC DATA ASSOCIATION IN DISTRIBUTED SENSOR NETWORKS
K.C. Chang, C.Y. Chong and Y. Bar-Shalom, Multisensor Integration and Fusion for intelligent Machines and Systems, edited by Ren C. Luo and Michael G. Kay, Ablex Publishing Corporation, Norwood, NJ

A distributed multitarget tracking problem is considered in this chapter. The Joint Probability Data Association (JPDA) algorithm, which has been successfully used for tracking multiple targets in a cluttered environment, assumes a centralized processing architecture. It assumes that measurements are transmitted to a central site and processed. In some applications, however, it may be desirable for the sensor measurements to be processed at or near the sensors instead of transmitting them to the central processor. The local processed results are then sent over a communication network to be used by other processor. This chapter presents a distributed version of the JPDA algorithm which is applicable under such a situation.